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Criterion analysis of heat and mass transfer in continuously cast steel slab

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Abstrakt: *An important area of the caster is the so-called secondary cooling zone, which is subdivided into thirteen sections. In the secondary-cooling zone, where the slab is beginning to straighten out the breakout of the steel can occur in points of increased local chemical and temperature heterogeneity of the steel, from increased tension as a result of the bending of the slab and also from a high local concentration of non-metal, slag inclusions. Especially dangerous are the changes in the chemical composition of the steel during the actual concasting. In the case of two melts one immediately after the other, i.e. when melt of steel of quality A finished and right now the melt of quality B followed, this could lead to interruption in the concasting and a breakout. The material, physical, chemical and technological parameters, which both melts differed in were determined. The parameters from the temperature field were calculated by means of the model, for example maximal and minimal lenghts of isoliquidai and isosolidai, the range of so-called mushy zone with temperature between liquidus and solidus, the temperature of surface slab and so on. The calculated parameters from the temperature field to the dimensionless criteria of similarity are obtained. If the dimensionless analysis is applied for assessing and reducing the number of these all parameters, then it is possible to express the level of risk of breakout as a function of five dimensionless criteria.*

1. Introduction

An increasing extent of oscillation marks and hooks leads to a defect in the shape of a crack, which reduces the thickness of the solidified shell of the slab upon its exit from the mould and causes a dangerous notch [1-3]. In the secondary-cooling zone, where the slab is beginning to straighten out, the breakout of the steel can occur in points of increased local chemical and temperature heterogeneity of the steel, from increased tension as a result of the bending of the slab and also a high local concentration of non-metal, slag inclusions. Especially dangerous are the changes in the chemical composition of the steel during the actual concasting.

2. Interruption of concasting

This case was recorded during the process of concasting of 250×1530 mm steel slabs of quality A with a 0.41 wt. % carbon content and 9.95 wt. % chromium content (melts 1 to 3) and quality B steel with 0.17 wt. % carbon content and 0.70 wt. % chromium content (melt 4). The change in the chemical compositions of the steels of both qualities was carried out very quickly by changing the tundish. In the unbending point of the slab, at a distance of 14.15 m away from the level of the melt inside the mould, on the small radius of the caster, occurred a breakout. A 250 mm thick sample was taken from the breakout area using a longitudinal axial cut (Fig. 1).

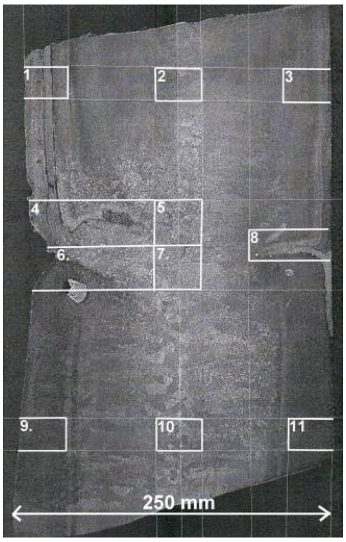

Fig.1: Macro-structure of breakout

The structure of this sample was analyzed and using the Bauman print the distribution of sulphur was analyzed too. The numbers 1 to 11 indicate the positions of the samples in the places around the breakout intended for analysis. Simultaneously, significant 25 mm sulphide segregations were discovered – very heterogeneous areas created by the original base material of the slab (melt 3), the new material of the slab (melt 4) and between them and also by the areas of mixed composition. Beneath the surface of the slab, at a depth of 75-to-85 mm, there were cracks and a zone of columnar crystals oriented towards the surface of the slab on the small radius. This was identical to the orientation of the groove which gradually turned into a crack (Fig. 1 – direction 4 – 6) and, on the opposite surface of the slab, the hook which was covered by melt (position 8). In the first phase of the analyses, the aim was to determine the material, physical, chemical and technological parameters, which both melts 3 and 4 differed in (besides the already introduced chemical composition). Table 1 contains the individual parameters of both melts.

3. Dimensionless criteria

If the method of dimensionless analysis is applied for assessing and reducing the number of parameters in Table 1 in the first approximation, then it is possible to express the level of risk of breakout as a function of the five dimensionless criteria contained in Table 2 (units m, kg, s, K).

Table 1. The parameters characterizing the concasting of melt 3 (quality A) and melt 4 (quality B)

Item #	Parameter	Symbol	Units	A – melt 3	B – melt 4
1	Pouring speed	w	[m.s^{-1}]	0.0130	0.0126
2	Dynamic viscosity	η $\eta = \rho.\nu$	[m^{-1}.kg.s^{-1}] [m^{-1}.kg.s^{-1}]	0.00570 T_L 0.00772 T_S	0.00562 T_L 0.00615 T_S
3	Density	ρ	[kg.m^{-3}]	7560.7	7600.9
4	Latent heat of the phase change	L	[m^2.kg.s^{-2}]	246×10^3	259×10^3
5	Specific heat capacity	c_p	[m^2.s^{-2}.K^{-1}]	632.6	611.0
6	Mould oscillation amplitude	ΔS	[m]	0.006±0.003	0.006±0.003
7	Oscillation frequency	f	[s^{-1}]	1.533	1.533
8	Solidus temperature	T_S	[°C]	1427.0	1480.6
9	Liquidus temperature	T_L	[°C]	1493.9	1512.3
10	Difference between the liquidus and solidus temperatures	$T_L - T_S$	[°C]	66.9	31.7
11	Max. length of the isosolidus curve from the level*	h_S^{max}	m	21.07	19.72
12	Min. length of the isosolidus curve from the level**	h_S^{min}	m	19.92	18.69
13	Max. length of the isoliquidus curve from the level*	h_L^{max}	m	14.50	16.20
14	Min. length of the isoliquidus curve from the level**	h_L^{min}	m	13.70	15.20
15	The area of the mushy zone on half of the cross-section of the breakout $^{+}$	F_{mushy}	m^2	0.05366	0.04100
16	The surface temperature of the slab^{++}	T_{surf}	°C	934	1097

Note (continued from table above): *) of the steel inside the mould to a position 0.650 m from the edges of the 1.53 m wide slab; **) of the steel inside the mould to the centre of the slab; $^{+}$) the overall area of half of the cross-section is F_{slab} = 0,19125 m^2 ; $^{++}$) in the material 15 mm around the groove (Fig. 1). The data in Table 1 were established a) on the caster after breakout; b) from archived on-line results of the temperature model; c) by off-line modelling of the temperature field of melts 3 and 4 [5].

Table 2. Dimensionless criteria characterizing the breakout

Criterion	$\frac{L.f}{c_p.\eta.T_L.\Delta S}$	$\frac{\Delta S.f}{w}$	$\frac{\rho.\Delta S^2.f}{\eta}$	$\frac{F_{slab}}{F_{slab}-F_{mushy}}$	$\frac{T_L-T_S}{T_L}$
steel A	5124.78	1.179	172.77	1.3900	0.044782
steel B	6237.96	1.217	197.87	1.2729	0.056404*

Note: *) The maximum temperature difference inside the mixture zone $(T_{L-B}-T_{S-A})/T_{L-B}$

4. Susceptibility to breakout – breakout risk

The risk of breakout grows in accordance with the first criterion directly proportionally to the latent heat *L* released from the mushy zone and inversely proportionally to its dynamic viscosity η. The second criterion (the Strouhal number) includes transient, oscillation movement including the amplitude of the mould and also, implicitly, a susceptibility to marks and hooks, which precede breakout. The third criterion has a similar significance but, in addition, includes also dynamic viscosity. The first three criteria increase the risk of breakout with melt 4 more than with melt 3. The fourth criterion characterizes the reduction of the load-bearing cross-section of the slab (by 28.1 % in melt 3 and by 21.4 % in melt 4) by creating a mushy zone, which indicates a greater risk of breakout in melt 3. The last criterion considers the effect of the mixture zone of melt 3 and a common effect of the mixture zone of melts 3 and 4. The first three criteria are of a dynamic nature and their product in melt 3 is 1.044×10^6 while in the fourth melt it is 1.502×10^6, i.e. the mixture melt has a 50 % greater risk of breakout. The product of all five criteria of melts 3 and 4, considering their partial homogenization, is 1.078×10^5 in melt 4 and 6.498×10^4 in melt 3. The quotient of the product for melts 3 and 4 is 0.603, which predicts a reduced risk of breakout in melt 3. If the influence of temperature on the surface of the slab in melt 3, and in the place of the groove in melt 4 it is clear that the effect of the groove during the straightening out of the slab is connected with tensile stress, then in the place of the groove (Fig. 1) the effect must have been compensated for at a temperature of 1097 °C, i.e. at a temperature 163 °C higher than that of a completely straight surface of the slab of melt 3. The data was obtained from the investigation into the causes behind a transversal crack that occurred in a different steel slab [4]. In order to clarify this, it was necessary to conduct a series of ductility tests at temperatures ranging from 20 °C to the solidus temperature. Table 3 contains the test results from temperatures that are close to the temperatures in row 16 of Table 2. A comparison of the mechanical values indicates that the tensile strength at 914.5 °C and the pulling force are 1.5× greater than at 1093.0 °C. In addition to this, there was a 8.605 m column of melt working on the mushy zone in the point of the breakout, where the mushy zone reached $h_S^{\max}$ =21.07 m from the level in the mould, i.e. at least 6.92 m beyond the breakout point. It is therefore possible to assume that the main factor that significantly increased the risk of breakout was the superposition of the causing effects of the parameters occurring in the first four criteria of Table 2.

Tab. 3. Ductility testing at 1093.0 and 914.5 °C [5]

Sample	Testing temperature [°C]	Tensile strength [N]	Strength [MPa]	Diameter [mm]	Contraction [%]	Deformation before breaking [mm]	Breaking Work [J]
1	1093	817	28.9	3.90	58.0	12.0	7
2	914.5	1247	44.1	5.35	21.5	5.5	6

5. Discussion and conclusion

Following a fast change of the tundish, there was a period of 20 min when there was a mixture of quality A and quality B steels. The liquidus temperature 1493.9 °C of quality A increased to 1512.3 °C and, simultaneously, the latent heat of the phase change increased from 246 kJ/kg (quality A) to 259 kJ/kg (quality B). This led to an increase in the temperature of the melt and to the re-melting of the solidified shell of the original quality A steel. Furthermore, there was an increase in the length of the mushy zone (up to $h_{S-3.tmelt}^{\max} - h_{L-3.melt}^{\min}$ = 21.07 – 13.70 = 7.37 m) and also in its temperature heterogeneity. The temperature of the mushy zone – following the mixing of both qualities – could find itself anywhere between the maximum temperature of the liquidus of quality A and the minimum temperature of the solidus of quality B (i.e. within the interval $T_{L-B} - T_{S-A}$= 1512.3 – 1427.0 = 85.3 °C. During the 20 min of pouring of the quality B steel (the 4th melt), which began immediately after the quality A steel (the 3rd melt), marks and hooks formed as a result of the oscillation of the mould and continued to form during the unbending of the slab (Fig. 1 – where the groove is 50 mm wide and 15-16 mm deep with an opening angle of 115 °). The tensile forces in the vicinity of this groove and the re-melting of the solidified shell brought about the breakout in the wall of the small radius of the slab in the unbending point.

One way of reducing the risk of breakout and the successive shutdown of the caster is to modify the values of the parameters in the first criterion in Table 2, i.e. to select two consecutive melts of such chemical compositions and the corresponding physical and chemical parameters (from which the dimensionless criteria are determined) that the criteria predict zero-breakthrough.

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